

CLAIMS

- 1 1. A storage medium that contains instructions executable by a computer system to
2 configure the computer system as a garbage collector that reclaims for reuse memory al-
3 located by a mutator executing on the computer system, wherein the garbage collector
4 performs a plurality of successive marking cycles, in each of which the garbage collector:
 - 5 A) performs a marking operation in which the garbage collector traces refer-
6 ence chains from a root set and makes marks associated with respective
7 objects thereby encountered;
 - 8 B) thereafter performs a succession of collection space increments within the
9 marking cycle;
 - 10 C) repeatedly calculates a measure of the cumulative efficiency of collection
11 that has taken place during the marking cycle and determines whether the
12 cumulative efficiency thereby calculated satisfies a set of at least one
13 marking-initiation criterion; and
 - 14 D) if so, terminates that marking cycle and begins the next marking cycle.
- 1 2. A storage medium as defined in claim 1 wherein one said marking-initiation crite-
2 rion is that the cumulative efficiency has peaked.
- 1 3. A storage medium as defined in claim 2 wherein one said marking-initiation crite-
2 rion is that at least a threshold number of collections have occurred during the marking
3 cycle.
- 1 4. A storage medium as defined in claim 1 wherein the cumulative collection effi-
2 ciency for a marking cycle is calculated as the ratio of an amount of memory reclaimed
3 during that marking cycle to an amount of time taken to by collection during that marking
4 cycle.

1 5. A storage medium as defined in claim 4 wherein, in determining the amount of
2 memory reclaimed in a cycle, the garbage collector includes the memory reclaimed by all
3 space-incremental-collection operations that take place after the end of that marking op-
4 eration.

1 6. A storage medium as defined in claim 5 wherein:
2 A) the garbage collector treats the heap as divided into regions; and
3 B) the marking operation includes reclaiming regions in which all objects sat-
4 isfy an unreachability criterion based on that marking operation's results.

1 7. A storage medium as defined in claim 6 wherein, in determining the amount of
2 memory reclaimed in a cycle, the garbage collector includes the amount of memory re-
3 claimed as part of the marking cycle's marking operation but omits any memory re-
4 claimed by any space-incremental-collection operations that take place before the end of
5 that marking operation.

1 8. A storage medium as defined in claim 4 wherein one said marking-initiation crite-
2 rion is that the cumulative efficiency has peaked.

1 9. A storage medium as defined in claim 1 wherein:
2 A) each of a plurality of the collection space increments reclaims a collection
3 set within the heap; and
4 B) the garbage collector bases the collection set's selection on the marks
5 made by one said marking operation's results.

1 10. A storage medium as defined in claim 9 wherein:
2 A) the garbage collector treats the heap as divided into regions, for which it
3 maintains respective remembered sets that in the collection space incre-
4 ments it uses to determine whether objects in the collection set are referred

5 to from outside the collection set and are therefore potentially reachable;
6 and
7 B) the garbage collector additionally bases the collection set's selection on
8 the sizes of the remembered sets.

1 11. A storage medium as defined in claim 9 wherein one said marking-initiation crite-
2 rion is that the cumulative efficiency has peaked.

1 12. A storage medium as defined in claim 11 wherein the marking operation occurs at
2 least in part concurrently with the mutator's execution.

1 13. A storage medium as defined in claim 12 wherein in each of a plurality of the col-
2 lection space increments the garbage collector determines whether objects in an associ-
3 ated collection set within the heap satisfy an unreachability criterion based on the mark-
4 ing operation's results, evacuates potentially reachable objects from the collection set
5 without evacuating any object thus identified, and reclaims the collection set.

1 14. A storage medium as defined in claim 9 wherein the marking operation occurs at
2 least in part concurrently with the mutator's execution.

1 15. A storage medium as defined in claim 14 wherein in each of a plurality of the col-
2 lection space increments the garbage collector determines whether objects in an associ-
3 ated collection set within the heap satisfy an unreachability criterion based on the mark-
4 ing operation's results, evacuates potentially reachable objects from the collection set
5 without evacuating any object thus identified, and reclaims the collection set.

1 16. A storage medium as defined in claim 14 wherein one said marking-initiation cri-
2 terion is that the cumulative efficiency has peaked.

1 17. A storage medium as defined in claim 9 wherein in each of a plurality of the col-
2 lection space increments the garbage collector determines whether objects in an associ-
3 ated collection set within the heap satisfy an unreachability criterion based on the mark-
4 ing operation's results, evacuates potentially reachable objects from the collection set
5 without evacuating any object thus identified, and reclaims the collection set.

1 18. A storage medium as defined in claim 17 wherein one said marking-initiation cri-
2 terion is that the cumulative efficiency has peaked.

1 19. A storage medium as defined in claim 1 wherein the marking operation occurs at
2 least in part concurrently with the mutator's execution.

1 20. A storage medium as defined in claim 19 wherein one said marking-initiation cri-
2 terion is that the cumulative efficiency has peaked.

1 21. A storage medium as defined in claim 19 wherein in each of a plurality of the col-
2 lection space increments the garbage collector determines whether objects in an associ-
3 ated collection set within the heap satisfy an unreachability criterion based on the mark-
4 ing operation's results, evacuates potentially reachable objects from the collection set
5 without evacuating any object thus identified, and reclaims the collection set.

1 22. A storage medium as defined in claim 1 wherein in each of a plurality of the col-
2 lection space increments the garbage collector determines whether objects in an associ-
3 ated collection set within the heap satisfy an unreachability criterion based on the mark-
4 ing operation's results, evacuates potentially reachable objects from the collection set
5 without evacuating any object thus identified, and reclaims the collection set.

1 23. A storage medium as defined in claim 22 wherein one said marking-initiation cri-
2 terion is that the cumulative efficiency has peaked.

- 1 24. For reclaiming for reuse memory allocated by a mutator executing on the com-
2 puter system, a method comprising employing the computer system to performs a plural-
3 ity of successive marking cycles, each of which includes:
- 4 A) performing a marking operation by tracing reference chains from a root set
5 and making marks associated with respective objects thereby encountered;
6 B) thereafter performing a succession of collection space increments within
7 the marking cycle;
8 C) repeatedly calculating a measure of the cumulative efficiency of collection
9 that has taken place during the marking cycle and determining whether the
10 cumulative efficiency thereby calculated satisfies a set of at least one
11 marking-initiation criterion; and
12 D) if so, terminating that marking cycle and beginning the next marking cy-
13 cle.
- 1 25. A method as defined in claim 24 wherein one said marking-initiation criterion is
2 that the cumulative efficiency has peaked.
- 1 26. A method as defined in claim 25 wherein one said marking-initiation criterion is
2 that at least a threshold number of collections have occurred during the marking cycle.
- 1 27. A method as defined in claim 24 wherein the cumulative collection efficiency for
2 a marking cycle is calculated as the ratio of an amount of memory reclaimed during that
3 marking cycle to an amount of time taken to by collection during that marking cycle.
- 1 28. A method as defined in claim 27 wherein, the memory reclaimed by all space-
2 incremental-collection operations that take place after the end of that marking operation
3 is included in determining the amount of memory reclaimed in a cycle.
- 1 29. A method as defined in claim 28 wherein:
2 A) the method includes treating the heap as divided into regions; and

- 3 B) the marking operation includes reclaiming regions in which all objects sat-
4 isfy an unreachability criterion based on that marking operation's results.

1 30. A method as defined in claim 29 wherein, the amount of memory reclaimed as
2 part of the marking cycle's marking operation is included in determining the amount of
3 memory reclaimed in a cycle, but the amount of memory reclaimed by any space-
4 incremental-collection operations that take place before the end of that marking operation
5 is not.

1 31. A method as defined in claim 27 wherein one said marking-initiation criterion is
2 that the cumulative efficiency has peaked.

1 32. A method as defined in claim 24 wherein:

- 2 A) each of a plurality of the collection space increments reclaims a collection
3 set within the heap; and
4 B) the collection set's selection is based on the marks made by one said
5 marking operation's results.

1 33. A method as defined in claim 32 wherein the method includes:

- 2 A) treating the heap as divided into regions and maintaining therefor respec-
3 tive remembered sets that in the collection space increments are used to
4 determine whether objects in the collection set are referred to from outside
5 the collection set and are therefore potentially reachable; and
6 B) additionally basing the collection set's selection on the sizes of the re-
7 membered sets.

1 34. A method as defined in claim 32 wherein one said marking-initiation criterion is
2 that the cumulative efficiency has peaked.

1 35. A method as defined in claim 34 wherein the marking operation occurs at least in
2 part concurrently with the mutator's execution.

1 36. A method as defined in claim 35 wherein each of a plurality of the collection
2 space increments includes determining whether objects in an associated collection set
3 within the heap satisfy an unreachability criterion based on the marking operation's re-
4 sults, evacuating potentially reachable objects from the collection set without evacuating
5 any object thus identified, and reclaiming the collection set.

1 37. A method as defined in claim 32 wherein the marking operation occurs at least in
2 part concurrently with the mutator's execution.

1 38. A method as defined in claim 37 wherein each of a plurality of the collection
2 space increments includes determining whether objects in an associated collection set
3 within the heap satisfy an unreachability criterion based on the marking operation's re-
4 sults, evacuating potentially reachable objects from the collection set without evacuating
5 any object thus identified, and reclaiming the collection set.

1 39. A method as defined in claim 37 wherein one said marking-initiation criterion is
2 that the cumulative efficiency has peaked.

1 40. A method as defined in claim 32 wherein each of a plurality of the collection
2 space increments includes determining whether objects in an associated collection set
3 within the heap satisfy an unreachability criterion based on the marking operation's re-
4 sults, evacuating potentially reachable objects from the collection set without evacuating
5 any object thus identified, and reclaiming the collection set.

1 41. A method as defined in claim 40 wherein one said marking-initiation criterion is
2 that the cumulative efficiency has peaked.

1 42. A method as defined in claim 24 wherein the marking operation occurs at least in
2 part concurrently with the mutator's execution.

1 43. A method as defined in claim 42 wherein one said marking-initiation criterion is
2 that the cumulative efficiency has peaked.

1 44. A method as defined in claim 42 wherein each of a plurality of the collection
2 space increments includes determining whether objects in an associated collection set
3 within the heap satisfy an unreachability criterion based on the marking operation's re-
4 sults, evacuating potentially reachable objects from the collection set without evacuating
5 any object thus identified, and reclaiming the collection set.

1 45. A method as defined in claim 24 wherein each of a plurality of the collection
2 space increments includes determining whether objects in an associated collection set
3 within the heap satisfy an unreachability criterion based on the marking operation's re-
4 sults, evacuating potentially reachable objects from the collection set without evacuating
5 any object thus identified, and reclaiming the collection set.

1 46. A method as defined in claim 45 wherein one said marking-initiation criterion is
2 that the cumulative efficiency has peaked.

1 47. A computer system configured by stored instructions as a garbage collector that
2 reclaims for reuse memory allocated by a mutator executing on the computer system,
3 wherein the garbage collector performs a plurality of successive marking cycles, in each
4 of which the garbage collector:

- 5 A) performs a marking operation in which the garbage collector traces refer-
6 ence chains from a root set and makes marks associated with respective
7 objects thereby encountered;
8 B) thereafter performs a succession of collection space increments within the
9 marking cycle;

- 10 C) repeatedly calculates a measure of the cumulative efficiency of collection
11 that has taken place during the marking cycle and determines whether the
12 cumulative efficiency thereby calculated satisfies a set of at least one
13 marking-initiation criterion; and
14 D) if so, terminates that marking cycle and begins the next marking cycle.

1 48. A computer system as defined in claim 47 wherein one said marking-initiation
2 criterion is that the cumulative efficiency has peaked.

1 49. A computer system as defined in claim 48 wherein one said marking-initiation
2 criterion is that at least a threshold number of collections have occurred during the mark-
3 ing cycle.

1 50. A computer system as defined in claim 47 wherein the cumulative collection effi-
2 ciency for a marking cycle is calculated as the ratio of an amount of memory reclaimed
3 during that marking cycle to an amount of time taken to by collection during that marking
4 cycle.

1 51. A computer system as defined in claim 50 wherein, in determining the amount of
2 memory reclaimed in a cycle, the garbage collector includes the memory reclaimed by all
3 space-incremental-collection operations that take place after the end of that marking op-
4 eration.

1 52. A computer system as defined in claim 51 wherein:

- 2 A) the garbage collector treats the heap as divided into regions; and
3 B) the marking operation includes reclaiming regions in which all objects sat-
4 isfy an unreachability criterion based on that marking operation's results.

1 53. A computer system as defined in claim 52 wherein, in determining the amount of
2 memory reclaimed in a cycle, the garbage collector includes the amount of memory re-

3 claimed as part of the marking cycle's marking operation but omits any memory re-
4 claimed by any space-incremental-collection operations that take place before the end of
5 that marking operation.

1 54. A computer system as defined in claim 50 wherein one said marking-initiation
2 criterion is that the cumulative efficiency has peaked.

1 55. A computer system as defined in claim 47 wherein:

- 2 A) each of a plurality of the collection space increments reclaims a collection
3 set within the heap; and
4 B) the garbage collector bases the collection set's selection on the marks
5 made by one said marking operation's results.

1 56. A computer system as defined in claim 55 wherein:

- 2 A) the garbage collector treats the heap as divided into regions, for which it
3 maintains respective remembered sets that in the collection space incre-
4 ments it uses to determine whether objects in the collection set are referred
5 to from outside the collection set and are therefore potentially reachable;
6 and
7 B) the garbage collector additionally bases the collection set's selection on
8 the sizes of the remembered sets.

1 57. A computer system as defined in claim 55 wherein one said marking-initiation
2 criterion is that the cumulative efficiency has peaked.

1 58. A computer system as defined in claim 57 wherein the marking operation occurs
2 at least in part concurrently with the mutator's execution.

1 59. A computer system as defined in claim 58 wherein in each of a plurality of the
2 collection space increments the garbage collector determines whether objects in an asso-

3 ciated collection set within the heap satisfy an unreachability criterion based on the mark-
4 ing operation's results, evacuates potentially reachable objects from the collection set
5 without evacuating any object thus identified, and reclaims the collection set.

1 60. A computer system as defined in claim 55 wherein the marking operation occurs
2 at least in part concurrently with the mutator's execution.

1 61. A computer system as defined in claim 60 wherein in each of a plurality of the
2 collection space increments the garbage collector determines whether objects in an asso-
3 ciated collection set within the heap satisfy an unreachability criterion based on the mark-
4 ing operation's results, evacuates potentially reachable objects from the collection set
5 without evacuating any object thus identified, and reclaims the collection set.

1 62. A computer system as defined in claim 60 wherein one said marking-initiation
2 criterion is that the cumulative efficiency has peaked.

1 63. A computer system as defined in claim 55 wherein in each of a plurality of the
2 collection space increments the garbage collector determines whether objects in an asso-
3 ciated collection set within the heap satisfy an unreachability criterion based on the mark-
4 ing operation's results, evacuates potentially reachable objects from the collection set
5 without evacuating any object thus identified, and reclaims the collection set.

1 64. A computer system as defined in claim 63 wherein one said marking-initiation
2 criterion is that the cumulative efficiency has peaked.

1 65. A computer system as defined in claim 47 wherein the marking operation occurs
2 at least in part concurrently with the mutator's execution.

1 66. A computer system as defined in claim 65 wherein one said marking-initiation
2 criterion is that the cumulative efficiency has peaked.

1 67. A computer system as defined in claim 65 wherein in each of a plurality of the
2 collection space increments the garbage collector determines whether objects in an asso-
3 ciated collection set within the heap satisfy an unreachability criterion based on the mark-
4 ing operation's results, evacuates potentially reachable objects from the collection set
5 without evacuating any object thus identified, and reclaims the collection set.

1 68. A computer system as defined in claim 47 wherein in each of a plurality of the
2 collection space increments the garbage collector determines whether objects in an asso-
3 ciated collection set within the heap satisfy an unreachability criterion based on the mark-
4 ing operation's results, evacuates potentially reachable objects from the collection set
5 without evacuating any object thus identified, and reclaims the collection set.

1 69. A computer system as defined in claim 68 wherein one said marking-initiation
2 criterion is that the cumulative efficiency has peaked.

1 70. An electromagnetic signal that represents instructions executable by a computer
2 system to configure the computer system as a garbage collector that reclaims for reuse
3 memory allocated by a mutator executing on the computer system, wherein the garbage
4 collector performs a plurality of successive marking cycles, in each of which the garbage
5 collector:

- 6 A) performs a marking operation in which the garbage collector traces refer-
7 ence chains from a root set and makes marks associated with respective
8 objects thereby encountered;
- 9 B) thereafter performs a succession of collection space increments within the
10 marking cycle;
- 11 C) repeatedly calculates a measure of the cumulative efficiency of collection
12 that has taken place during the marking cycle and determines whether the
13 cumulative efficiency thereby calculated satisfies a set of at least one
14 marking-initiation criterion; and

15 D) if so, terminates that marking cycle and begins the next marking cycle.

1 71. An electromagnetic signal as defined in claim 70 wherein one said marking-
2 initiation criterion is that the cumulative efficiency has peaked.

1 72. An electromagnetic signal as defined in claim 71 wherein one said marking-
2 initiation criterion is that at least a threshold number of collections have occurred during
3 the marking cycle.

1 73. An electromagnetic signal as defined in claim 70 wherein the cumulative collec-
2 tion efficiency for a marking cycle is calculated as the ratio of an amount of memory re-
3 claimed during that marking cycle to an amount of time taken to by collection during that
4 marking cycle.

1 74. An electromagnetic signal as defined in claim 73 wherein, in determining the
2 amount of memory reclaimed in a cycle, the garbage collector includes the memory re-
3 claimed by all space-incremental-collection operations that take place after the end of that
4 marking operation.

1 75. An electromagnetic signal as defined in claim 74 wherein:

- 2 A) the garbage collector treats the heap as divided into regions; and
3 B) the marking operation includes reclaiming regions in which all objects sat-
4 isfy an unreachability criterion based on that marking operation's results.

1 76. An electromagnetic signal as defined in claim 75 wherein, in determining the
2 amount of memory reclaimed in a cycle, the garbage collector includes the amount of
3 memory reclaimed as part of the marking cycle's marking operation but omits any mem-
4 ory reclaimed by any space-incremental-collection operations that take place before the
5 end of that marking operation.

1 77. An electromagnetic signal as defined in claim 73 wherein one said marking-
2 initiation criterion is that the cumulative efficiency has peaked.

1 78. An electromagnetic signal as defined in claim 70 wherein:

2 A) each of a plurality of the collection space increments reclaims a collection
3 set within the heap; and

4 B) the garbage collector bases the collection set's selection on the marks
5 made by one said marking operation's results.

1 79. An electromagnetic signal as defined in claim 78 wherein:

2 A) the garbage collector treats the heap as divided into regions, for which it
3 maintains respective remembered sets that in the collection space incre-
4 ments it uses to determine whether objects in the collection set are referred
5 to from outside the collection set and are therefore potentially reachable;
6 and

7 B) the garbage collector additionally bases the collection set's selection on
8 the sizes of the remembered sets.

1 80. An electromagnetic signal as defined in claim 78 wherein one said marking-
2 initiation criterion is that the cumulative efficiency has peaked.

1 81. An electromagnetic signal as defined in claim 80 wherein the marking operation
2 occurs at least in part concurrently with the mutator's execution.

1 82. An electromagnetic signal as defined in claim 81 wherein in each of a plurality of
2 the collection space increments the garbage collector determines whether objects in an
3 associated collection set within the heap satisfy an unreachability criterion based on the
4 marking operation's results, evacuates potentially reachable objects from the collection
5 set without evacuating any object thus identified, and reclaims the collection set.

1 83. An electromagnetic signal as defined in claim 78 wherein the marking operation
2 occurs at least in part concurrently with the mutator's execution.

1 84. An electromagnetic signal as defined in claim 83 wherein in each of a plurality of
2 the collection space increments the garbage collector determines whether objects in an
3 associated collection set within the heap satisfy an unreachability criterion based on the
4 marking operation's results, evacuates potentially reachable objects from the collection
5 set without evacuating any object thus identified, and reclaims the collection set.

1 85. An electromagnetic signal as defined in claim 83 wherein one said marking-
2 initiation criterion is that the cumulative efficiency has peaked.

1 86. An electromagnetic signal as defined in claim 78 wherein in each of a plurality of
2 the collection space increments the garbage collector determines whether objects in an
3 associated collection set within the heap satisfy an unreachability criterion based on the
4 marking operation's results, evacuates potentially reachable objects from the collection
5 set without evacuating any object thus identified, and reclaims the collection set.

1 87. An electromagnetic signal as defined in claim 86 wherein one said marking-
2 initiation criterion is that the cumulative efficiency has peaked.

1 88. An electromagnetic signal as defined in claim 70 wherein the marking operation
2 occurs at least in part concurrently with the mutator's execution.

1 89. An electromagnetic signal as defined in claim 88 wherein one said marking-
2 initiation criterion is that the cumulative efficiency has peaked.

1 90. An electromagnetic signal as defined in claim 88 wherein in each of a plurality of
2 the collection space increments the garbage collector determines whether objects in an
3 associated collection set within the heap satisfy an unreachability criterion based on the

4 marking operation's results, evacuates potentially reachable objects from the collection
5 set without evacuating any object thus identified, and reclaims the collection set.

1 91. An electromagnetic signal as defined in claim 70 wherein in each of a plurality of
2 the collection space increments the garbage collector determines whether objects in an
3 associated collection set within the heap satisfy an unreachability criterion based on the
4 marking operation's results, evacuates potentially reachable objects from the collection
5 set without evacuating any object thus identified, and reclaims the collection set.

1 92. An electromagnetic signal as defined in claim 91 wherein one said marking-
2 initiation criterion is that the cumulative efficiency has peaked.

1 93. A garbage collector for reclaiming for reuse memory allocated by a mutator exe-
2 cuting on the computer system, the garbage collector including:

- 3 A) means for performing a marking operation by tracing reference chains
4 from a root set and making marks associated with respective objects
5 thereby encountered;
- 6 B) means for thereafter performing a succession of collection space incre-
7 ments within the marking cycle;
- 8 C) means for repeatedly calculating a measure of the cumulative efficiency of
9 collection that has taken place during a marking cycle that begins with the
10 marking operation and determining whether the cumulative efficiency
11 thereby calculated satisfies a set of at least one marking-initiation crite-
12 rion; and
- 13 D) means for, if so, terminating that marking cycle and beginning a subse-
14 quent marking cycle.